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Derivation of Technology Specific Effects of the Use of Oxygenated Fuel Blends on Motor Vehicle Exhaust Emissions

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Technical Report

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16. ABSTRACT

This report is a supporting document to the repot, "Guidance on Estimating Motor Vehicle Emission Reductions from the Use of Alternative Fuels and Fuel Blends" (January 1988). It presents the data and calculations which were used to estimate the effects of gasoline/oxygenate fuel blends on vehicle exhaust emissions. Data were gathered from several studies of fuel blends, and include tests of blends with methanol, ethanol, tert-butyl alcohol, and MTBE. Effects are calculated separately for vehicles with different emission control technology. The report discusses exhaust emissions of hydrocarbons, carbon monoxide, and oxides of nitrogen.

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1.0 INTRODUCTION

In the past decade there has been a large amount of research into the effects of fuel composition on the emissions of motor vehicles. Blends of gasoline with oxygenates such as alcohols and ethers have received particular attention, and it has been widely demonstrated that use of these blends can reduce emissions of carbon monoxide (CO). Some organizations have proposed that this beneficial effect could help alleviate CO air quality problems which have been experienced in some areas. It has also been shown that such blends can affect exhaust and evaporative emissions of volatile organic compounds (VOC) and exhaust emissions of oxides of nitrogen (NOx). The blends generally cause small increases in NOx emissions, and they can cause increases or reductions in the net emissions of VOC, depending on the blending components and volatility of the final product. State and local governments have proposed including programs of increased use of these blends in their plans in order to help local areas meet the National Ambient Air Quality Standard for CO.

To assist local and state planners in considering this issue, EPA has developed guidance for estimating the fleetwide effects that these fuels can have on vehicular emissions of CO, VOC, and NOx. The technical report, "Guidance on Estimating Motor Vehicle Emission Reductions from the Use of Alternative Fuels and Fuel Blends"[1], discusses EPA's procedure for estimating these fleetwide effects. A draft of the report was released for public comment in July, 1987, and the final version was released in January, 1988.

The procedure is based on estimates of the effects on emissions that gasoline/oxygenate blends can have on groups of vehicles within the fleet. This report discusses the methods and data which EPA used in calculating these estimates. Only the data used in the development of the guidance report are discussed here; no additional data have been included. Some errors in calculation (Data were duplicated on more than one reference) were discovered and corrected after the guidance report was released. Therefore, the effects which are presented here are different from those listed in the guidance report. These differences are small.

It should be noted that all of the calculation steps presented in this report are intermediate steps in a larger calculation described in the Guidance Report. To prevent the proliferation of truncation errors, numerical figures are not truncated to their known number of significant digits.

1.1 Effects of Fuel Oxygen Content; a General Discussion

Most vehicles meter fuel by volume with the goal of controlling the ratio of air to fuel. A useful reference point in discussing air/fuel ratios is the stoichiometric point, at which all of the fuel can theoretically react with the oxygen in the air. When the fuel control system of a vehicle puts too much fuel into the engine at a time (a condition known as "running rich"), there will not be enough oxygen to allow complete combustion of the fuel. The result will be increased amounts of the products of incomplete combustion, CO and VOC, in the exhaust. Most gasoline fueled engines run rich some of the time, and it is during this time that much of the emissions of these pollutants occur.

The feature of gasoline/alcohol and gasoline/ether blends which has the largest effect on emissions is oxygen content. When these fuels are used, the oxygen in the fuel reduces the amount of air needed to burn a given amount of fuel in two ways. It increases the amount of oxygen which is available for combustion, and it displaces some of the carbon which would otherwise consume oxygen. This effect is called "enleanment." A vehicle which uses a gasoline/oxygenate blend fuel will spend less time running rich, and will have less severe richness during that time than when it uses a non-oxygenated fuel. A vehicle which spends a large portion of its operating time in a rich mode will have higher base emissions than another vehicle which is seldom running rich. The use of oxygenated blends will cause a larger reduction in the emissions of the former vehicle than the latter.

1.2 Quantifying These Effects

It is difficult to quantify the effects of fuel oxygen on exhaust emissions both in terms of predicting the effects on the emissions of a vehicle and in terms of predicting the effects on the emissions of a fleet of vehicles. This difficulty stems from the wide variety of other factors which affect emissions and can interact with fuel oxygen content to further affect emissions. Such factors include, but are not limited to the age of the vehicle, the emission control technology used in the vehicle design, the maintenance history of the vehicle, the ambient operating temperature, the altitude of operation, the initial calibration of the fuel metering system, and the fuel volatility. A further complicating factor is the wide range of emission levels from different vehicles in a given fleet and the non-normal distribution of these levels. These issues are discussed in more detail in Section 3.

EPA has examined many studies in an attempt to predict the effects that gasoline/oxygenate blend fuels will have on vehicle emissions. This document presents in a consistent form all available and relevant data which EPA has used in its examination of this issue. Also discussed are the methods which EPA used to evaluate these data, and the conclusions which EPA has drawn from this effort.

2.0 THE DATA BASE

EPA applied a number of criteria to the data from each known vehicle test program before including it in the data base. To be included, each program had to report emissions data from Federal Test Procedures performed on vehicles using at least two different fuels. Preferably, one of these fuels would be similar to non-oxygenated gasolines currently available at retail outlets, while the other fuel(s) would represent a gasoline/oxygenate blend which could be sold at a retail outlet. EPA excluded data on vehicles using certain fuel blends, such as blends of ethanol in greater than 10 percent concentrations, blends of methanol in greater than 5 percent concentrations, and blends of methanol without cosolvents. In one case a low level methanol/cosolvent blend was excluded because it had an unrepresentatively low RVP of 8.0 psi. The data include test results from high and low altitude facilities, results of tests on light duty and heavy duty gasoline fueled vehicles and trucks, results of tests using blends of gasoline with ethanol, MTBE, and methanol/cosolvent. No data from low temperature emission tests are included. The resulting data base includes tests of about 350 vehicles in 21 studies.

2.1 Sources

EPA has considered data which were found in its own extensive literature searches, as well as all of the data which were brought to light by commenters to the July 1987 draft of the report, "Guidance on Estimating Motor Vehicle Emission Reductions from the Use of Alternative Fuels and Fuel Blends". The data were gathered by State and Federal governmental testing programs, programs conducted by the petroleum and automobile industries, and independent testing laboratories. Two organizations offered large lists of additional sources of data.

Energy and Environmental Analysis, Inc. (EEA) submitted a report which it prepared for the Maricopa Association of Governments, "Feasibility of Using Alternative Fuels as an Air Pollution Control Strategy,"[2] which contains a list and grouped analysis of thirty-two studies. Some of the data contained in these studies were excluded from EPA's final analysis because of the characteristics of the fuels which they used, as was discussed previously, but other studies referenced in this list provided EPA with additional information about the effects of blends at high altitudes and emissions of vehicles using fuels with intermediate levels of oxygen content. (An oxygen content of 3.7% by weight is the maximum allowable under existing regulations. Some blends, especially those which contain MTBE, have oxygen contents close to 2.0%.) Nine of the studies cited by EEA are directly included in EPA's data base. Several others are referenced in a summary study which EPA also included.

The Ad Hoc Ethanol Committee submitted extensive comments including a list of thirteen studies. There was considerable overlap between this list and the references of the EEA report. The EPA data base was expanded to include six additional studies from this list. Most of these compare a blend of 10% ethanol with gasoline. A large proportion of the vehicles covered have open loop fuel control.

EPA received additional data from the Colorado Department of Health (CDH)[5] during the comment period, some of which were also referenced in the EEA report. The testing programs of CDH have provided the majority of EPA's information on the effects of blends at high altitude. They cover a wide range of vehicle technologies and fuel types.

The CDH laboratory and more recently EPA's Office of Mobile Sources have conducted testing programs on the effects of long term use of gasoline/oxygenate blends in late model vehicles with "adaptive learning systems." These systems increase the control of vehicle designers over the air/fuel ratio during the operation of the vehicle. Some vehicle manufacturers have claimed that these systems can almost completely negate the effects of fuel oxygen content on emissions after the vehicle has used a blend for a certain amount of time. These two laboratories have been testing vehicles equipped with such systems, and the results of these tests are also included in this analysis.

3.0 ISSUES IN ANALYSIS OF DATA

EPA considered several issues in the process of analyzing the data. Since the database includes information from so many studies of different fuels and vehicles, care must be taken to combine the results in a manner which will give the best approximation of the fleetwide effects of a particular fuel. It is also important to separate groups of data in which vehicles could be expected to respond in different ways to the presence of oxygenates in fuel. Factors which were considered when forming these groups are discussed later in this report.

3.1 Choosing a Model for Effects on Emissions

A model must be developed which predicts the emission effects of oxygenated fuel blends within each appropriately segregated vehicle group. These effects will be weighted and combined as described in Appendix D of the Guidance Document. There are several ways in which these effects could be modeled. The simplest of these is to assume that a given oxygenated blend causes an offset, in grams per mile, above or below the base emission level. This model is easy to develop and apply, but, as has been discussed before, vehicles with already low emissions should not, theoretically, see as much of an absolute reduction as a group of high emitters.

Another simple model could predict emissions changes in each group as a constant percentage of the base emissions. In this model, high emitters would achieve a larger absolute change than low emitters. This model is consistent with other models which have been developed[4], but it does not allow for the possibility that vehicles with already very low emissions would see little or no benefit from the enleanment effect of blends.

It has been proposed[2] that quadratic or other non-linear models could be used to describe the effect of oxygen content on emissions. There are two problems with this approach. The first is in developing the model; there is so much scatter in the data that deciding which model to use and determining the parameters of such a model can be a difficult and arbitrary procedure. The other problem with non-linear models (and even linear but non-proportional models) is that their application to a fleet is a complicated process. To apply a non-linear model properly it is necessary to know the distribution of emissions within a given group and integrate the results of the model over the whole group. It would be very difficult to predict and to use the emissions distributions of the many groups that would be required to obtain a fleetwide effect. EPA's emission factor model, MOBILE3, does not provide such distributions.

EPA has elected to use the model of percentage changes. The average emission reduction for the portion of the vehicle fleet of a given type is taken to be a constant percentage of those vehicles' base emissions on oxygen free gasoline, regardless of average base emissions, age, odometer, speed, and ambient temperature. The constant percentage is calculated as described below from the available test data on vehicles of the given type. This model fits observed patterns in the data better than the constant mass reduction model, and it is easier to apply than a non-linear model would be.

Most analyses of emission data have used the technique of comparing means to report emission changes. At least one report (EEA) has used regression techniques to make predictions of emissions changes which depend on the base emissions themselves. EPA recognizes the advantages that regression techniques can offer in such analyses, such as the separation of the effects of several independent variables. However, the results present among the studies which EPA considered were widely scattered and not normally distributed. Curve fitting techniques are less convincing when applied to data such as emissions results which are not normally distributed and have large amounts of scatter. Therefore, EPA has elected to use the simpler technique of finding changes in mean results.

The primary drawback to this method is that there is no way to perform statistical tests of significance. Since the data are lumped together in groups of different sizes (the number of vehicles tested in each study varies widely), and since many of the study wide means are reported without information about their respective variances, there is no way to examine the distribution of individual points in the data base. Therefore, the interpreted significance of many of the effects which will be discussed in this report must be based on engineering judgement. It is likely that such judgement would be equally important even if all of the individual data points were known, because of the non-normality of emissions distributions and the wide ranges of emissions from different vehicles, which would make statistical tests less valid than they would otherwise be.

3.2 Combining Many Studies in a Single Database

EPA has attempted in this analysis to combine the results of as many studies as possible in a consistent manner so that the aggregate could be extrapolated to in-use vehicles. In this process, EPA was careful to consider the differences among the studies and between the studies and in-use conditions.

The emission levels of the vehicles used in many of the individual studies are not representative of emissions which occur with in-use vehicles. Table 1 shows the emission levels which EPA's mobile source emission factor model (MOBILE3) predicts for vehicles operating at low altitude in 1990. Three vehicle classes are shown: light duty gasoline fueled vehicles, and two classes of light duty gasoline fueled trucks. (Trucks in the LDGT1 class weigh 6000 lbs or less, and LDGT2 includes trucks which weigh between 6000 and 8500 lbs.) Within each vehicle class, the vehicles are split into groups by model year, to represent the different emission control technologies which have been most common in different model years.

Table 1

Emissions of In-Use Vehicles in 1990*

	No Catalyst	Oxidation Catalyst	Closed Loop/3way	Recent Cl Loop/3way
LDGV				
Model yrs	1968-74	1975-80	1981-83	1984+
HC (g/mi)	6.15	4.16	1.57	0.66
CO (g/mi)	80.44	47.90	21.97	8.97
NOx (g/mi)	3.98	3.36	1.71	1.04
LDGT1				
Model yrs	1968-74	1975-83	1984-87	1988+
HC (g/mi)	6.94	5.41	1.82	1.00
CO (g/mi)	89.58	58.05	20.12	12.08
NOx (g/mi)	4.13	3.88	2.54	1.38
LDGT2				
Model yrs	1968-78	1979-83	1984-87	1988+
HC (g/mi)	9.02	5.01	1.86	1.01
CO (g/mi)	99.94	51.21	20.52	12.19
NOx (g/mi)	5.61	3.83	2.58	1.39

* As predicted by MOBILE3 for vehicles operating at low altitude with no I/M or anti-tampering program in effect. High altitude operation causes increased emissions of HC and CO. I/M and anti-tampering programs cause the levels of HC and CO emissions to be lower.

Many of the studies which EPA examined had vehicle groups with average CO emissions close to 2 grams/mile. The emissions measured in these studies clearly do not represent in-use distributions. Table 1 shows that even among relatively new vehicles the average emissions are close to or higher than 9 grams/mile. However, under the percentage change model selected by EPA, the base emission level should not, strictly speaking, affect the percentage change. Given the extreme differences between the emissions of the test samples and the in-use vehicles they are taken to represent for purposes of calculating percent changes, EPA kept alert for possible contradictions as it proceeded through the analysis.

EPA considered whether to use individual test results or to find some way to group the data before performing any statistical observations. For example, the EEA summary report[2] used as the basic unit of observation the percentage reduction in the average emissions of a given vehicle when using a given fuel blend. While many of the reports included individual test results, some included only averages. Using the results of individual tests would require that data from some testing programs be eliminated from the data base. Entering all of the available individual test results into a data base would have required a large effort while adding little additional information. As will be discussed in the next section, EPA divided the total data base into subgroups, based on technology features of the vehicles and the test programs in which the data were gathered. EPA elected to use study-wide reductions in the average emissions of groups of vehicles operating on a given fuel. In other words, these reductions were recorded, and statistical analyses were performed on the groups' reductions. To give extensive studies a larger effect on the final results than more limited ones, each study is considered to have a weight within a technology group equal to the number of vehicles of that group which were used in the program.

To summarize the procedure, the data are divided into groups, as will be explained in Section 3.3. The emissions of vehicles which are in the same study and group are averaged for all cases in which they use the same fuel. The averages of vehicles using an oxygenated fuel blend are compared to the averages of the same vehicles when operating on an HC-only fuel and expressed as a percentage change. Each of these percentage changes are normalized to represent fuels with matched volatilities and constant oxygen content, as will be shown in Section 3.3.4. When vehicles in the same study used more than one oxygenated fuel blend, the percentage reductions are averaged over all of the fuel blends for that study. The resulting changes are averaged over an entire group, with the results of each study weighted by the number of vehicles represented in the group.

3.3 Subdividing the Data Base

There are factors which change the way the presence of oxygenates in vehicle fuel affects emissions. These factors fall into three categories; features of the vehicle (such as emission control technology and fuel delivery system), fuel attributes (volatility and oxygen content), and ambient conditions (altitude and temperature). EPA decided to examine the interactions between these effects and to subdivide the data base when appropriate so that the effects could be calculated separately. EPA has been careful keep the data groups as large as possible; conclusions drawn on small samples of emissions data may not be very accurate because of the wide variation in emission levels from different vehicles.

3.3.1 Technology

Perhaps the most important subdivision in this database is based on the vehicle technology. Since 1970 there have been several developments in emission control technology which may interact with the way oxygenated fuel blends affect emissions. The introduction of the oxidation catalytic converter in 1975 and then the widespread use of the three-way catalytic converter, starting in 1981, are examples. Since oxygenates have different products of combustion at a given air/fuel ratio than gasoline and since they tend to burn at different temperatures, it is reasonable to assume that a catalytic converter might behave differently in the exhaust stream of a blend fueled vehicle than in the exhaust of the same vehicle fueled with gasoline. EPA has chosen to examine the emissions of vehicles equipped with catalytic converters separately from those not so equipped.

A further development in technology has been the introduction of closed loop fuel control systems. Such systems readjust the air/fuel ratio during some phases of vehicle operation based on measurements of the oxygen concentration in the exhaust. Too much oxygen in the exhaust indicates that the mixture is too lean, while too little oxygen in the exhaust indicates that the mixture is rich. Closed loop fuel control, by maintaining a mixture that is close to stoichiometric, has been very effective at controlling emissions. Most vehicles which have three-way catalysts also have closed loop fuel control, and vice-versa. Such systems can, in theory, counteract the enleanment effect of the fuel oxygen content by adding more fuel. EPA has chosen to examine the effects of blends on the emissions of these systems separately from those of open loop (fuel controlled without measurements of exhaust) systems.

Some studies have separated vehicles with three-way catalytic converters and open loop fuel control from other groups. EPA considered this course of action and noted that three-way catalysts are similar to oxidation catalysts in their effect on VOC and CO. Oxidation catalysts often use some formulation of platinum and palladium as the catalytic material. Three-way catalysts usually have platinum and rhodium, and perhaps some palladium. Based on this similarity and the small amount of data on vehicles with open loop fuel control and three-way catalytic converters, EPA decided to group such vehicles together with open loop vehicles with oxidation catalysts.

Closed loop systems operate in an open loop mode under certain circumstances, such as cold starting, idling, or extreme acceleration, depending on the design. In such a mode, the air/fuel mixture is controlled based on some predetermined value, rather than a measurement of oxygen in the exhaust. Most closed loop vehicles use only fixed calibrations to set the air/fuel ratio when operating in an open loop mode. However, some new systems (available since about 1984) adjust the mixture during open loop mode based on electronically stored values from previous closed loop modes. These systems are said to have "adaptive learning" algorithms. Manufacturers do not routinely identify individual vehicles or even vehicle models as being equipped with an adaptive learning feature. Not all vehicles are, even in the latest model year. EPA has assumed that the mix of 1984 and later vehicles that have been tested in the various studies adequately represent the mix of adaptive and non-adaptive models in recent and future model years.

In theory, vehicles with adaptive learning systems should be less affected by oxygenates in the fuel than older style closed loop systems. In actuality, the proof must be sought in data, since vehicle designers have implemented the adaptive learning concept in different ways.

The last issue with respect to technology division was whether all closed loop vehicles that have been tested should be grouped together to represent the entire population of closed loop vehicles, including those from the most recent and future model years. The alternative would be to divide the closed loop test sample into "old technology" and "adaptive learning" (or "new technology" more generally) and use only the latter to represent the latest and future production vehicles. To test the emissions of such vehicles when operating on a gasoline/oxygenate blend fuel, it is important that the vehicles be operated with the fuel for a certain amount of time (which may vary for different vehicle designs) prior to the test.

EPA has examined separately the tests of vehicles of the 1984 and later model years which were tested with this preconditioning. The results of this comparison are shown in Table 2. EPA could not determine in all cases which vehicles actually did have adaptive learning systems and to what extent the systems operate during test conditions.

Table 2

Comparison of Effects;
Preconditioned* 1984 and Newer Vehicles Versus
Unpreconditioned and/or Pre-1984 Closed Loop Vehicles

Vehicle Group/ References	Emissions Changes on Oxygenated Fuels** N	HC	CO	NOx
Preconditioned 1984 and Newer B, G	50	-11.1%	-24.6%	+10.6%
Other Closed Loop C, E, J, S, U, V, W, X, Y, Z, AA, AB	88	-2.3%	-19.5%	+8.0%

* Preconditioning consists of use of a particular fuel in a vehicle for a certain amount of time (perhaps several LA4 test cycles) prior to the actual emissions test. Preconditioning procedures are those recommended by the vehicle manufacturers to each study's project manager.

** Results include high and low altitude data. Results normalized to matched RVP and 3.7% oxygen content.

Though the variance of the emissions was too large to perform statistical tests comparing the two groups in Table 2, it is possible to draw a meaningful conclusion from it. Theoretically, a vehicle with adaptive learning should be affected less by fuel oxygen content than a vehicle without. Thus, the null hypothesis would be that the vehicles without adaptive learning are not affected more than the vehicles which have such algorithms, and the data confirm this hypothesis. EPA concludes that to whatever extent adaptive learning is being used in production, it does not cause a significant change in the response to oxygenated fuels.

Though not a new technology, the use of fuel injection has become more common in new vehicles in recent years. Since it is difficult to separate data regarding vehicles with fuel injection from vehicles with carburetion (many of the studies do not record that information) and since engine control logic is probably more important than the mechanical approach, EPA elects to consider vehicles with both types of fuel systems as part of the same group in its analysis of exhaust emissions. It should be noted, however, that the fuel delivery system is important in the analysis of evaporative emissions.

3.3.2 Altitude

The data may also be subdivided by the altitude (high or low) at which they were collected. There is a large amount of information available on both altitudes, so sample sizes remain sufficiently large. At high altitude, a given volume of air contains less oxygen. Vehicles operating at high altitudes must compensate for the lack of oxygen, or they will run rich for a larger portion of their operating time than when they operate at low altitudes. The introduction of extra oxygen in the fuel can mitigate this effect. Fuel oxygen content theoretically should have an absolute effect on high altitude emissions that is greater than or equal to the effects at low emissions, but the percentage effect may be about the same. EPA has analyzed separately the data taken at high altitude. However, no studies are yet available which compare the emissions of the same vehicles at both high and low altitudes with oxygenated fuel blends.

Table 3

Emission Changes with Oxygenated
Blend Fuels* at High and Low Altitude

Vehicle Group	Altitude	Number of Vehicles	Effect of Blend on Emissions HC	CO	NOx
No ** Catalyst	High	24	-11.3%	-23.9%	+8.1%
	Low	24	+0.4%	-25.0%	+3.8%
Oxidation Catalyst	High	63	-15.8%	-31.4%	+6.5%
	Low	76	-15.3%	-37.3%	+2.2%
Closed Loop	High	46	-1.9%	-18.4%	+5.8%
	Low	76	-4.2%	-20.6%	+11.6%

* Results normalized to represent matched RVP fuels with 3.7% oxygen.

** Appendix A contains complete listings of the references used in generating this table.

As with the results listed in Table 2, it would be difficult to disprove a null hypothesis that the percentage effect at high altitude is larger than that at low altitude, because of the large variance in the data. However, the fact that the average effects on CO are larger for the low altitude tests of each vehicle type tends to confirm the null hypothesis for CO. Similarly, the hypothesis can be confirmed for all three pollutants from closed loop vehicles.

EPA believes that the data do not show a significant difference between the effects of fuel oxygen content at high and low altitudes, especially for CO which is of most interest to planners considering oxygenated fuels. EPA has elected to use data gathered at high and low altitudes together.

3.3.3 Oxygen Content

A potentially important issue is the difference between the effects of fuels with 3.7% oxygen content and those with 2% oxygen content. Blends of ethanol in gasoline which are currently sold at the retail level contain 3.7% oxygen. Gasoline/methanol blends are not currently marketed in the U.S., but they would generally be expected to contain about 3.7% oxygen. Blends of MTBE in gasoline may contain up to 2% oxygen, limited by EPA's decision that MTBE is "substantially similar" to gasoline and as such may be added in limited concentrations without a Clean Air Act waiver. It is generally accepted that the effects of fuel oxygen increase with increasing oxygen content, but the increase is not necessarily a linear relationship. Different studies have shown different trends in this respect. One may show that the benefit of the lower oxygen content fuel is larger than what would be predicted by a proportional model, while another shows that the benefit is smaller. After examining the data, EPA elected to assume that the effect on emissions is linearly (in fact, proportionately) related to oxygen content at least up to the 3.7% oxygen level, and the data are normalized to represent a constant oxygen content over the entire data base before averages are computed.

Planners will be considering as a pollution control strategy the mandated use of oxygenated blends. By specifying the amount of oxygen which will be required, they can effectively limit or allow certain blend types. By some measures, the cost (in terms of loss of consumer choice, vehicle effects, reduced price competition, loss of highway revenue through tax credits, etc.) of restricting the retail market to higher oxygen level fuels is high. Planners will want to be sure that sufficient additional emissions benefits are needed before incurring these additional costs.

More data exist on emissions effects with 3.7% oxygen fuels than with 2% oxygen fuels. There are several studies in which vehicles were tested with both levels of blends. There is enough variability in the results of these studies that the shape of a curve which relates oxygen content to emissions effects c uld only be arbitrarily determined. Such a curve would be based on the theoretical enleanment effects of the two types of fuels. The 2% oxygen fuel will provide a certain amount of enleanment during rich modes of operation. The enleanment might reduce the richness of some modes beyond the point of stoichiometry (after which additional enleanment has little additional effect). The additional enleanment of a 3.7% oxygen fuel will only further reduce emissions during operation modes that are still rich when using the 2% fuel. Thus, there would be some levelling off of the benefits at high oxygen contents. This argument would indicate that the 2% fuel has a larger effect than simply 2/3.7 of the effect of a 3.7% oxygen fuel (as would be predicted by an oxygen proportional model). However, given that vehicles often emit pollutants at higher levels than their certification standards even when using 3.7% oxygen fuel, it appears that there are still significant periods of rich operation. It seems reasonable to assume that most of the significant levelling off occurs at even higher levels of oxygen content. The correct answer to this question could vary with vehicle technology. EPA has chosen to assess these questions by examining the emissions of vehicles which have been tested with both fuels, accounting for other factors, such as RVP, which could otherwise affect the results.

Table 4

Comparison of Effects on RVP-Adjusted CO per Percent Oxygen; Two Levels of Oxygen Content

Vehicle Group/ References	N vehs**	Change from Base Emissions/%Ox* 2.0% oxygen	3.7% oxygen
No Catalyst/ E, H, AB	9	-7.8%	-4.9%
Open Loop/ E, R, S, U, V, AB	28	-10.5%	-8.8%
Closed Loop/ E, S, V, AB	25	-3.4%	-4.2%

* Effects listed are the actual effects after adjustment to to a constant RVP divided by the oxygen content of the fuels, which demonstrates the idea that the effect of the blend fuel is proportional to the oxygen content.

** Includes vehicles tested on fuels of both oxygen levels.

Table 4 shows the ratios of average CO effects to fuel oxygen content for three different technology types and two different oxygen levels. It shows that for vehicles with catalysts (both open and closed loop), the ratio stays roughly the same, regardless of the actual oxygen level. The constant ratio indicates that the effect of oxygen on these vehicles can be estimated as directly proportional to oxygen content. The sample size of the vehicles without catalytic converters which were tested on both fuels is small, so the comparison is less conclusive in their case. EPA has elected to extend the assumption of proportionality to these older vehicles. The null hypothesis that the ratio stays the same regardless of total oxygen content could not be disproved based on these data for any of the groups.

Since the time that the Guidance Document was released, EPA has tested more than sixty vehicles using fuels of two different oxygen levels. Data have become available from other sources as well, and this additional information will be considered in the next revision of the Guidance Document.

3.3.4 Other Fuel Related Factors; RVP and Oxygenate Species

Fuel related factors other than oxygen content may affect emissions. For example, it is well documented that the Reid Vapor Pressure (RVP) of the fuel can affect FTP exhaust emissions. Since the RVP of any large group of fuels forms a continuous spectrum, EPA has found no appropriate way to subdivide the data base to separate the effects of RVP from fuel oxygen content. Instead of subdividing the data base, EPA has elected to adjust emissions test data using known relations to volatility when RVP of the fuels are known (or can be reasonably assumed, since some reports do not include volatility information). The adjustment takes place before the percent changes between group means on two fuels are calculated. The adjustments are based on data from variable RVP tests in EPA's emission factor program. They were determined using only tests with gasoline, but EPA assumes that they also apply to gasoline/oxygenate blends. Few data are available to test this assumption, however. The following table shows the functions which EPA applied to make these adjustments.

Table 5

RVP adjustments from MOBILE3.9

Model Years 1971 - 1980 HC adjustment:

$$HC = (HC @11.5\ RVP) * (0.79622 + 0.01772(RVP))$$

Model Years 1981 and later HC adjustment:

$$HC = (HC @11.5\ RVP) * (0.57112 + 0.03729(RVP))$$

Model Years 1971 - 1980 CO adjustment:

$$CO = (CO @11.5\ RVP) * (0.65094 + 0.03035(RVP))$$

Model Years 1981 and later CO adjustment:

$$CO = (CO @11.5\ RVP) * (0.18753 + 0.07065(RVP))$$

MOBILE3.9 is the last version of the MOBILE3 emission factor model. It was intended to incorporate many of the ideas which will be included in the MOBILE4 model which is still under development as of this writing.

The model year groups above separate those years in which open loop and closed loop fuel control systems predominate. In the analysis of gasoline/oxygenate blends, the pre-1981 model year expression is applied to open loop vehicles, and the expression for 1981 and later model years is applied to closed loop vehicles.

The type of oxygenate used in a fuel blend might also have an effect on emissions. There are significant physical differences between the various oxygenates, such as polarity, miscibility with water, latent heat of vaporization, etc. EPA has attempted to determine the effect of the species of oxygenate (ethanol, methanol, MTBE, etc.) in the fuel blend on emissions independent of total fuel oxygen content. This is directly possible only for comparisons of ethanol blends with methanol blends, since blends with MTBE have lower oxygen contents than most blends with methanol or ethanol. This comparison can be made in paired tests with the relatively very few vehicles which received emissions tests using both types of fuels, as shown in Table 6.

Table 6

Paired Oxinol, TBA, and Gasohol Tests*

Vehicle Group	N Vehs	Fuel Blend	Changes in Emissions ** HC	CO	NOx
Oxidation Catalyst	8	10% EtOH	-35.4%	-47.3%	-4.5%
		16% TBA	-30.2%	-47.5%	-10.6%
		Oxinol	-33.9%	-49.6%	-13.1%
Closed Loop	3	10% EtOH	-28.8%	-49.0%	-3.8%
		16% TBA	-29.7%	-51.0%	-7.0%
		Oxinol	-19.7%	-29.2%	-10.8%

* Data taken from ARCO waiver request for Oxinol.

** Emissions changes are relative to emissions on non-oxygenated base gasoline.

The theoretical effect of oxygenate species (independent of oxygen content and volatility) is not well defined. EPA could find no empirical reason to separate the data by fuel-related factors other than volatility and oxygen content.

3.3.5 Ambient Temperature

Low ambient temperatures can extend the time that it takes for an engine to reach operating temperature. During this time, catalytic converters operate at less than peak efficiency, closed loop systems operate in open loop mode, and fuel control systems use a rich mixture to keep the engine from stalling. These effects may interact with the effects of fuel oxygen. EPA does not presently have enough data to characterize this interaction.

3.3.6 Base Emission Levels

While a percentage reduction model has a theoretical attraction (since higher base emissions imply that there are more modes with opportunity for enleanment), it may not strictly hold for extreme emission levels. Because the emission levels represented in the data (as shown in Appendix A) are so low compared to in-use levels (as shown in Table 1), this effect, if present, could reduce the accuracy of the extrapolations from the data to a fleet.

In EPA's analysis, the results of individual studies are kept distinct up to a point, so it is possible to look for a relationship between base emission levels and the percentage reductions. EPA could find no such relationship, but the difference between the emission levels of the different studies is not as great as the difference between the levels in that data base and in-use emissions. The reader is encouraged to examine the results in Appendix A to confirm this conclusion.

4.0 RESULTS

The following table shows the technology-specific effects on emissions that would be caused by switching from a non-oxygenated gasoline to a gasoline/oxygenate blend with the same volatility and a 3.7% oxygen content.

Table 7

Technology Specific Effects
on Emissions of a Fuel with 3.7%
Oxygen and Volatility Matched to Base Fuel

Vehicle Group	Number of Vehicles	Effect of Blend on Emissions		
		HC	CO	NOx
No Catalyst	48	-5.5%	-24.5%	+3.8%
Oxidation catalyst	160	-15.5%	-34.7%	+4.1%
Closed Loop	138	-2.3%	-19.5%	+3.0%

Note that these values are slightly different from those listed in Table 3-1 of the Guidance Document. The difference stems from an error which was found in the original data base after the final version of the document was published. The correction of this error yielded values which are in all cases but one within 0.3 percentage points of the values originally published. The estimate of the effect on NOx emissions from closed loop vehicles increased by 1.1 percentage points. EPA does not consider these corrections to be large enough to require re-issuing the Guidance Document. A complete listing of the data and sources used in developing these values is presented in Appendix A.

If the fuel has an oxygen content other than 3.7%, then these effects must be adjusted in proportion to the actual oxygen content. If the blend is of a different volatility than the fuel it replaces, then Table 5 should be used to adjust the resulting effect.

References

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4. "Ethanol-Blended Fuel as a CO Reduction Strategy at High Altitude," Section C, Vol. II, Colorado Department of Health, August 1985.

5. "Fleet Demonstration," Colorado Department of Health, November 1987.

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10. "Exhaust and Evaporative Emissions from a Brazilian Chevrolet Fueled with Ethanol-Gasoline Blends," R. Furey and M. Jackson, GM Research Publication GMR-2403, June 1977.

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17. "Gasohol, TBA, MTBE Effects on Light-Duty Emissions," B. Bykowski, Southwest Research Institute, EPA Report 460/3-79-012, NTIS PB 80224082, October 1979.

18. "Evaporative and Exhaust Emissions from Cars Fueled With Gasoline Containing Ethanol or MTBE," R. Furey and J. King, SAE Paper 800261.

19. "Performance Evaluation of Alcohol-Gasoline Blends in 1980 Model Automobiles: Phase 1 - Gasoline-Ethanol Blends," CRC Report No. 527, July 1982.

20. Clean Air Act Waiver Application for Oxinol, ARCO, May 1981.

21. Clean Air Act Waiver Application for the DuPont blend, July 11 1984.

22. "In-House 23 Car In-House Oxinol Blend Test Program," EPA memo from Craig Harvey to Charles Gray, ECTD, November 19, 1984.

23. "Characterization of Emissions from Vehicles Using Methanol and Methanol-Gasoline Blended Fuels," P. Gabele et al, JAPCA Vol. 35, no. 11, 1168-1175, 1985.

24. "A Generic Report of Toxics from Oxygenated Fuels," Colorado Department of Health, Spring 1987; Note: CDH has stated these preliminary data are released for use in our report.

Appendix A

Data and Sources

I. No Catalyst

Altitude	Ref #	#Vehs	# Alt Fuels	Notes	Emissions on Base Fuel in (g/mi) RVP	VOC	CO	NOx	Splash 10% EtOH RVP	VOC%	CO%	NOX%
high	A	10	1	all HDV's		4.66	60.50	3.33	N.D.	-14.6%	-23.7%	5.0%
high	B	4	1	CDH fleet demo	vars	2.72	72.97	3.53				
high	D	2	1	big cars	9.0	4.00	89.60	2.59	?	-8.2%	-19.8%	20.1%
high	AB	4	2	CDH Toxics	10.7	5.29	61.94	1.30				
high	E	4	2	Trucks	10.8	5.91	109.30	3.42				
High Total		24										
low	d	1	3	very approx		3.00	120.00	0.50		-15.0%	-16.6%	60.0%
low	P	1	1			1.50	25.40	1.93		-2.0%	-50.0%	-23.0%
low	T	22	1	mostly LDT's		4.58	32.30	4.60		2.8%	-22.3%	-2.8%
Low Total		24										
TOTAL Non-Cat		48										

II. Ox cat. Open loop

Altitude	Ref #	#Vehs	# Alt Fuels	Notes	Emissions on Base Fuel in (g/mi) RVP	VOC	CO	NOx	Splash 10% EtOH RVP	VOC%	CO%	NOX%
high	B	4	1	CDH fleet demo	vars	2.45	63.38	1.77	vars			
high	b	7	1	other vehs	vars	1.42	38.80	1.62	vars			
high	C	33	1		9.9	1.42	24.73	1.32	9.8	-16.4%	-34.8%	8.3%
high	D	8	1	large engines	9.0	2.06	31.76	1.49		-23.4%	-24.8%	2.4%
high	AB	9	2	CDH Toxics	10.7	1.91	27.4	2.38				
high	E	9	2	CDH Oxinl/MTBE	10.8	3.06	55.70	1.97				
High Total		70										
low	J	24	1	tests not matched	9.0	0.80	6.77	1.53	9.6	-16.4%	-39.0%	11.6%
low	j	19	1	comm base fuel	10.0	0.83	9.95	1.59	10.9	-20.9%	-32.6%	7.4%
low	R	2	3		9.3	0.86	10.44	2.41	10.2	-23.3%	-39.5%	-2.5%
low	S	5	1		8.6	[illegible]	[illegible]	1.53				
low	s	5	1	other blend	8.6	0.85	6.56	1.53				
low	T	31	1	fleet tests		2.08	14.80	3.36		13.0%	-34.5%	-6.6%
low	U	2	1		9.1	0.63	7.58	0.97				
low	u	2	1	other blend	9.1	0.63	7.58	0.97				
low	V	1	2		9.0	0.65	6.52	1.79	9.7	-13.5%	-28.1%	-22.3%
low	W	7	2		9.6	0.27	4.67	1.43	10.5	0.0%	-25.3%	16.8%
low	w	7	1	other blend	9.6	0.27	4.67	1.43				
low	X	8	2	ARCO waiver	12.5	0.96	20.40	1.98	13.0	-35.4%	-47.3%	-4.5%
low	x	8	1	other blend	12.5	0.96	20.40	1.98				
low	Y	3	1	DuPont	9.2	0.53	6.67	1.90				
low	y	1	1	other blend	9.2	0.16	3.20	1.02				
low	Z	7	1	EPA 23 car	11.6	0.54	5.43	0.99				
Low Total		90										
TOTAL Open Loop		160										

III. Closed loop (pre '84 model year or not preconditioned)

Altitude	Ref #	#Vehs	# Alt Fuels	Notes	Emissions on Base Fuel in (g/mi) RVP	VOC	CO	NOx	Splash 10% EtOH RVP	VOC%	CO%	NOX%
high	C	19	1		9.0	0.47	6.21	5.68	9.6	-1.8%	-13.6%	7.9%
high	AB	7	2	CDH Toxics	10.7	0.58	10.39	0.97				
high	E	13	2	CDH Oxinl/MTBE	10.8	0.61	7.30	[illegible]				
High Total		39										
low	J	11	1	Indol base	9.0	0.34	4.36	0.66	9.6	-6.2%	-19.4%	3.7%
low	j	9	1	commerc base	10.0	0.37	5.70	0.55	10.9	11.6%	-7.5%	6.5%
low	K	1	1	very approx		0.27	2.60	0.38		-22.2%	-23.1%	13.0%
low	S	3	1		8.6	0.43	6.23	0.48				
low	s	3	1	other blend	8.6	0.43	6.23	0.48				
low	U	1	1		9.1	0.24	3.41	0.79				
low	u	1	1	other blend	9.1	0.24	3.41	0.79				
low	V	[illegible]	2	prototype vehs	[illegible]	0.23	1.88	[illegible]	9.7	13.0%	3.7%	1.4%
low	W	7	2		9.6	0.30	5.08	0.62	10.5	16.7%	-26.0%	11.3%
low	w	[illegible]	1	other blend	9.6	0.30	5.08	0.52				
low	X	3	2	ARCO waiver	12.5	0.37	5.78	1.57	13.0	-28.8%	-49.0%	-3.8%
low	x	3	1	other blend	12.5	0.37	5.78	1.57				
low	Y	5	1	DuPont	9.2	0.22	3.44	0.72				
low	y	2	1	other blend	9.2	0.21	2.65	1.04				
low	Z	14	1	EPA 23 car	11.6	0.55	5.59	0.91				
low	AA	2	1	RTP	11.7	0.44	4.60	1.08				
Low Total		49										
TOTAL		88										

IV. Closed loop (84+ model year, preconditioned)

Altitude	Ref #	#Vehs	# Alt Fuels	Notes	Emissions on Base Fuel in (g/mi) RVP	VOC	CO	NOx	Splash 10% EtOH RVP	VOC%	CO%	NOX%
high	B	[illegible]	1	CDH fleet demo	vars	0.63	16.41	1.33				
high	C	10	1	different vehs	vars	0.37	[illegible]	[illegible]				
low	F	33	1	EPA In-house	11.7	0.55	7.41	0.79				
TOTAL		50										

Emission Changes caused by blend use

Other Fuel ~3.7% Ox						Other Fuel, ~2% Ox					
type	%Oxy	RVP	VOC%	CO%	NOx%	type	%Oxy	RVP	VOC%	CO%	NOx%
splash EtOH	3.2	vars	3.1%	-16.2%	15.7%						
E10 adj	3.7	10.2	-14.6%	-20.6%	-1.0%	11% MTBE	2	10.5	-1.1%	-11.6%	-4.5%
Oxinol50	3.5	11	-12.0%	-21.4%	-0.9%	11% MTBE	2	9.8	-14.4%	-23.8%	16.4%
E10 adj	3.7	adjus	-15.0%	-20.8%	60.0%	5%EtOH splash	1.9		-7.5%	-6.3%	40.0%

Emission Changes caused by blend use

Other Fuel ~3.7% Ox						Other Fuel, ~2% Ox					
type	%Oxy	RVP	VOC%	CO%	NOx%	type	%Oxy	RVP	VOC%	CO%	NOx%
splash EtOH	2.92	vars	10.0%	-19.0%	21.3%						
						MTBE 1 - 2%	1.54	vars	-13.2%	-12.0%	-3.1%
E10 adj	3.7	10.2	-7.9%	-32.5%	5.5%	11% MTBE	2	10.5	0.7%	-11.9%	4.0%
Oxinol50	3.5	11	-2.6%	-22.4%	1.0%	11% MTBE	2	9.8	-14.1%	-21.5%	8.1%
E10 adj	3.7	10	-2.2%	-26.5%	7.7%						
E10 adj	3.7	9.4	-6.1%	-34.7%	-21.6%	5% EtOH	1.9	10.4	2.3%	-4.2%	2.5%
						7% MTBE	1.3	8.7	-20.0%	-32.5%	-0.6%
						7% TBA	1.5	9.1	-6.2%	-7.9%	7.4%
						7% MTBE	1.3		-7.7%	-39.7%	10.0%
						7% TBA	1.5		-10.3%	-44.8%	10.0%
E10 adj	3.7	9	-21.5%	-32.7%	-26.3%	15% MTBE	2.7	9.1	-20.0%	-25.9%	-21.8%
E10 adj 2	3.7	9.4	-7.4%	-45.6%	23.8%						
E10 adj 3	3.7	9.4	-7.4%	-29.1%	22.4%						
TBA16	3.5	12.4	-30.2%	-47.5%	-10.6%						
Oxinol	3.7	14.9	-33.9%	-49.6%	-13.1%						
Fuel 82	3.7	9.1	-18.9%	-41.5%	-4.4%						
Fuel93(E10)	3.7	9.1	-12.5%	-26.1%	-1.0%						
Oxinol	3.5	11.2	7.4%	-14.5%	18.2%						

Emission Changes caused by blend use

Other Fuel ~3.7% Ox						Other Fuel, ~2% Ox					
Type	%Oxy	RVP	VOC%	CO%	NOx%	Type	%Oxy	RVP	VOC%	CO%	NOx%
E10 adj	3.7	10.2	4.3%	-11.5%	-2.4%	11% MTBE	2	10.5	-1.8%	-3.8%	-0.6%
Oxinol 50	3.5	11	5.2%	-16.4%	-2.7%	11% MTBE	2	9.6	3.3%	-9.6%	10.7%
E10 adj	3.7	10	18.9%	-0.3%	11.0%						
						7% MTBE	1.3	8.7	-27.9%	-27.6%	35.0%
						7% TBA	1.5	9.1	-25.5%	-21.5%	20.8%
						7%TBA	1.5		-26.7%	-39.6%	0.0%
						7% MTBE	1.3		-26.7%	-34.4%	2.0%
E10 adj	3.7	9	15.0%	33.3%	0.0%	15% MTBE	2.7	9.1	-4.3%	2.7%	6.4%
E10 adj 2	3.7	9.4	-13.3%	-43.9%	19.4%						
E10 adj 3	3.7	9.4	0.0%	-19.7%	16.1%						
TBA16	3.5	12.4	-29.7%	-51.0%	-7.0%						
Oxinol	3.7	14.9	-19.7%	-29.2%	-10.8%						
Fuel 82	3.7	9.1	-4.5%	-24.4%	-5.6%						
Fuel93(E10)	3.7	9.1	9.5%	-35.8%	-1.9%						
Oxinol	3.5	11.2	7.3%	-10.6%	2.2%						
Oxinol(hiRVP)	3.5	12.9	-20.5%	1.1%	0.9%						

Emission Changes caused by blend use

Other Fuel ~3.7% Ox						Other Fuel, ~2% Ox					
Type	%Oxy	RVP	VOC%	CO%	NOx%	Type	%Oxy	RVP	VOC%	CO%	NOx%
splash EtOH	3.27	vars	-22.4%	-30.3%	-3.8%						
						MTBE 1 - 2%	1.84	vars	-8.1%	-13.1%	0.9%
E10 adj	3.7	11.8	-5.3%	-21.5%	16.3%						

Calculations: Account for Different Oxygen Content and Volatility

	Forcing Matched RVP Splash 10% Ethanol			Forcing Matched RVP & Oxy from other 3.7 Ox fuels				Forcing Matched RVP & 2% Ox from 2%Ox				Forcing 3.7% Ox from 2% fuels		
Ref #	D psi	VOC%	CO%	D psi	VOC%	CO%	NOx%	D psi	VOC%	CO%	NOx%	VOC%	CO%	NOx%
A	0.76	-15.6%	-25.5%											
B				0.8	1.0%	-21.0%	16.2%							
[illegible]	0.76	-9.4%	-21.7%											
AB				0.5	-13.9%	-19.4%	-1.0%	-0.2	-0.7%	-11.0%	-4.5%	-1.3%	-20.4%	-6.2%
E				0.2	-13.0%	-23.1%	-1.0%	-1.0	-12.9%	-21.5%	15.4%	-23.8%	-39.8%	30.3%
H	0.76	-16.1%	-18.5%	0.0	-25.0%	-23.8%	30.0%	0.7	-4.2%	-10.8%	42.1%	-16.8%	-20.0%	77.9%
P	0.76	-3.3%	-31.2%											
T	0.76	1.4%	-24.1%											

Calculations: Account for Different Oxygen Content and Volatility

	Forcing Matched RVP Splash 10% Ethanol			Forcing Matched RVP & Oxy from other 3.7 Ox fuels				Forcing Matched RVP & 2% Ox from 2%Ox				Forcing 3.7% Ox from 2% fuels		
Ref #	D psi	VOC%	CO%	D psi	VOC%	CO%	NOx%	D psi	VOC%	CO%	NOx%	VOC%	CO%	NOx%
B				0.8	10.8%	-26.4%								
b								0.0	-17.1%	-15.6%	-4.0%	-31.7%	-28.8%	-7.4%
C	0.80	-17.6%	-36.4%											
D	0.76	-24.4%	-26.5%											
AB				-0.5	-7.1%	-31.5%	5.5%	-0.2	1.1%	-11.3%	4.0%	2.0%	-20.9%	7.4%
E				0.2	-3.1%	-24.2%	1.1%	-1.0	-12.6%	-19.1%	3.1%	-23.3%	-35.4%	15.0%
J	0.60	-17.3%	-40.1%											
[illegible]	0.90	-22.2%	-34.4%	0.0	-2.2%	-26.5%	7.7%							
R	0.76	-24.3%	-40.9%	0.1	-6.3%	-34.9%	-21.6%	0.1	[illegible]	-7.8%	1.6%	0.6%	-14.4%	4.9%
[illegible]								0.1	-31.8%	-30.0%	-0.9%	-57.3%	-93.1%	-1.7%
S								0.5	-12.0%	-12.4%	0.9%	22.2%	-22.9%	18.3%
T	0.75	-14.2%	-36.0%											
[illegible]								0.0	-11.2%	-61.1%	15.4%	-21.9%	-100.0%	28.5%
[illegible]								0.0	-13.7%	-59.7%	13.3%	-25.4%	-100.0%	24.7%
U	0.70	-19.5%	-29.6%	0.0	-21.5%	-32.7%	-26.3%	0.1	-14.9%	-19.4%	-16.1%	-27.6%	-35.8%	-29.9%
W	0.90	-1.6%	-27.3%	0.2	[illegible]	-45.3%	23.8%							
w				-0.2	-7.1%	-28.7%	22.4%							
X	0.50	-36.0%	-48.1%	-0.1	-31.6%	-50.0%	-11.2%							
x				0.4	-36.7%	-53.3%	-13.1%							
Y				-0.1	-13.8%	-41.3%	-4.4%							
y				-0.1	-12.3%	-27.9%	-1.0%							
Z				0.4	[illegible]	-14.2%	19.2%							

	Calculations: Account for Different Oxygen Content and Volatility														
	Forcing Matched RVP Splash 10% Ethanol			Forcing Matched RVP & Oxy from other 3.7 Ox fuels				Forcing Matched RVP & 2% Ox from [illegible]Ox				Forcing 3.7% Ox from 2% fuels		
Ref #	D psi	VOC%	CO%	D psi	VOC%	CO%	NOx%	D psi	VOC%	CO%	NOx%	VOC%	CO%	NOx%
C	0.80	-4.7%	-23.2%											
BB				-0.5	5.2%	-5.4%	-1.4%	-0.2	-2.1%	-2.5%	-0.6%	-3.8%	-4.5%	-1.1%
E				0.2	7.8%	-16.6%	-1.9%	-1.0	7.2%	-3.2%	10.7%	13.2%	-5.9%	19.8%
J	0.60	-8.3%	-22.8%											
[illegible]	0.90	7.9%	-13.4%	0.0	18.9%	-4.3%	11.0%							
K	0.76	-24.4%	-27.2%											
[illegible]								0.1	-43.3%	-43.2%	53.8%	60.2%	-80.0%	99.6%
S								0.5	-35.9%	-32.4%	27.7%	-66.3%	-59.9%	51.3%
U								0.0	-35.6%	-52.8%	0.0%	-65.9%	-97.7%	0.0%
[illegible]								0.0	-41.1%	-52.9%	3.1%	-76.0%	-97.9%	5.7%
V	0.70	10.1%	-1.4%	0.0	15.0%	33.3%	0.0%	0.1	-3.4%	1.5%	4.7%	-6.4%	2.7%	8.8%
W	0.90	12.8%	-30.7%	-0.2	-12.7%	-43.1%	19.4%							
[illegible]				-0.2	0.7%	-18.6%	16.1%							
[illegible]	0.50	-30.1%	-50.8%	-0.1	-31.1%	-53.5%	-7.4%							
X				2.4	-26.9%	-41.2%	-10.8%							
Y				-0.1	-4.1%	-23.9%	-5.6%							
Y				-0.1	0.9%	-35.3%	-1.9%							
Z				-0.4	9.4%	-8.5%	2.3%							
AA				1.2	-25.4%	-7.9%	1.0%							

	Calculations: Account for Different Oxygen Content and Volatility														
	Forcing Matched RVP Splash 10% Ethanol			Forcing Matched RVP & Oxy from other 3.7 Ox fuels				Forcing Matched RVP & 2% Ox from [illegible]Ox				Forcing 3.7% Ox from 2% fuels		
Ref #	D psi	VOC%	CO%	D psi	VOC%	CO%	NOx%	D psi	VOC%	CO%	NOx%	VOC%	CO%	NOx%
E				0.8	-27.8%	-38.5%	-4.3%							
[illegible]								0.0	-6.8%	-14.2%	1.0%	-16.3%	-26.3%	1.8%
G				0.1	-6.0%	-22.1%	16.3%							

Average reductions by study
matched 3.7% Ox and RVP.
weighted together by veh

#	VOC%	CO%	NOx%	Base g/mi VOC	Base g/mi CO	Base g/mi NOx
A	-1[illegible].8%	-25.5%	5.0%			
B	[illegible].0%	-21.0%	13.2%			
C	-9.4%	-21.7%	20.1%			
AB	-7.6%	-19.9%	-4.6%			
E	-18.4%	-31.4%	14.7%			
Hi alt tot	-11.4%	-24.5%	8.5%	4.60	61.73	3.10
H	-19.3%	-19.8%	[illegible]2.6%			
P	-3.3%	-51.2%	-23.0%			
T	1.4%	-24.1%	-2.8%			
Lo alt tot	0.4%	-25.0%	-0.5%	4.59	35.67	4.32
Total	-5.5%	-24.8%	4.0%	4.59	56.70	3.71

Average reductions by study
matched 3.7% Ox and RVP,
weighted together by veh

#	VOC%	CO%	NOx%	Base g/mi VOC	Base g/mi CO	Base g/mi NOx
B	10.8%	-26.4%	0.0%			
b	-31.7%	-28.8%	-7.4%			
C	-17.6%	-36.4%	8.3%			
D	-24.4%	-26.5%	2.4%			
AB	-2.5%	-26.2%	6.4%			
E	-13.2%	-29.8%	8.0%			
Hi alt tot	-15.7%	-31.8%	5.3%	1.83	33.47	1.62
I	-17.3%	-40.1%	11.6%			
J	-12.2%	-30.5%	7.6%			
R	-10.7%	-30.1%	-6.4%			
S	-57.3%	-93.1%	-1.7%			
s	-22.2%	-22.9%	18.3%			
T	-14.2%	-36.0%	-8.6%			
U	-21.9%	-100.0%	28.5%			
u	-25.4%	-100.0%	24.7%			
V	-22.9%	-32.7%	-26.2%			
W	-4.3%	-36.3%	20.3%			
w	-7.1%	-28.7%	12.4%			
X	-33.9%	-49.1%	-7.9%			
x	-36.7%	-53.3%	-13.1%			
Y	-18.8%	-41.3%	-4.4%			
y	-12.3%	-27.9%	-1.0%			
Z	8.6%	-14.2%	19.2%			
Lo alt tot	-15.3%	-37.5%	2.2%	1.26	11.34	2.18
total	-15.4%	-35.0%	3.6%	1.46	21.02	1.93

Average reductions by study
matched 3.7% Ox and RVP.
weighted together by veh

#	VOC%	CO%	NOx%	Base g/mi VOC	Base g/mi CO	Base g/mi NOx
[illegible]	-4.7%	-23.2%	7.9%			
AB	1.2%	-6.5%	-1.7%			
E	10.5%	-12.3%	3.5%			
hi alt tot	1.4%	-16.6%	5.4%	0.53	8.30	3.60
[illegible]	-8.3%	-22.8%	3.7%			
[illegible]	13.4%	-6.8%	3.8%			
[illegible]	-24.4%	-27.2%	13.0%			
[illegible]	-30.2%	-30.0%	39.6%			
[illegible]	-66.3%	-59.9%	51.3%			
U	-65.9%	-97.7%	0.0%			
i	-76.0%	-97.9%	5.7%			
[illegible]	6.2%	11.5%	3.4%			
[illegible]	1.1%	-36.9%	15.4%			
W	0.7%	-18.6%	16.1%			
[illegible]	-30.6%	-52.2%	-3.6%			
X	-26.9%	-41.2%	-10.8%			
Y	-4.1%	-23.9%	-5.6%			
y	9.9%	-35.3%	-1.9%			
Z	9.4%	-8.5%	2.3%			
AA	-25.4%	-7.9%	1.0%			
lo alt tot	-5.1%	-22.2%	9.3%	0.39	4.95	0.80
Total	-2.2%	-19.7%	6.0%	0.45	6.43	2.13

Average reductions by study
matched 3.7% Ox and RVP.
weighted together by veh

#	VOC%	CO%	NOx%	Base g/mi VOC	Base g/mi CO	Base g/mi NOx
[illegible]	-17.8%	-38.5%	4.3%			
[illegible]	-16.3%	-26.3%	1.6%			
[illegible]	-6.6%	-22.1%	16.3%			
both alt	11.5%	-25.2%	10.5%	0.52	9.71	0.93
all CL	-5.6%	-21.7%	3.9%	0.5	7.6	1.7

Pages A-1 through A-8 list all of the data which were used in this report. These pages also show results at intermediate steps in the calculations which lead to the report's conclusions. The information is presented as a spreadsheet, so the easiest way to look at the entire process is to separate the pages from the report and tape them together side by side in the following arrangement (although it is possible to follow the process without doing so):

Page A-1	Page A-3	Page A-5	Page A-7
Page A-2	Page A-4	Page A-6	Page A-8

The data on vehicles without catalytic converters and vehicles with oxidation catalysts and open loop fuel control are on odd numbered pages (top row), while the even numbered pages have the data concerning all of the vehicles with closed loop fuel control. The following is an explanation of the columns in the spreadsheet:

Altitude: Indicates the altitude at which each study is conducted. Most of the high altitude studies were conducted in the Denver area by the Colorado Department of Health.

Ref #: The letter shown in this column indicates the study from which the data in each row was taken. The letter/study key is listed on the last pages of this Appendix. Lower case letters indicate that the row is a second entry for the study in the previous row. Studies are listed in more than one entry whenever they include more than one fuel of the same general type, such as two different gasoline/methanol blends. Also, if a study includes vehicles of different emission control groups, the study is indicated (with a capital letter) in each emission control group in this table. Some letters are skipped because the studies which would have been indicated by those letters are already represented in a summary study. Though some vehicles are represented twice in this and the next column, all operations which add the results of different studies together are designed to count the results from each vehicle only once.

#Vehs: This column indicates the number of vehicles which are represented in the row.

Alt Fuels: Indicates the number of gasoline/oxygenate blends which are represented in the row.

Notes: Notes were included to help keep track of important points regarding each study.

Emissions on Base Fuel: The four columns under this heading list the RVP of the base fuel, when known, and the average exhaust VOC, CO, and NOx emissions of all the vehicles in the group when tested on the non-oxygenated base fuel.

Splash 10% EtOH: The four columns under this heading are filled only when the vehicles represented on the row were tested on a splash blend of gasoline with 10% ethanol. The columns list the RVP of the blend and the percent reductions in the exhaust emissions of VOC, CO, and NOx relative to the levels in the previous columns (base fuel).

Other Fuel ~3.7% Ox: The six columns under this heading are filled only when the vehicles were tested on a blend of fuel with an oxygen content of more than 3.0%, but which is not a splash blend of ethanol. Such a blend might be a volatility adjusted blend of gasoline with 10% ethanol or a blend of gasoline with 5% methanol and a cosolvent. The columns name the fuel, list its RVP and oxygen content, and show the average emissions reductions relative to the base fuel which were reported when the fuel was used.

Other Fuel ~2% Ox: The columns under this heading are analogous to those listed under the previous heading, but are included only when vehicles were tested with a fuel of about 2% oxygen content, such as a blend of 11% MTBE or 5% ethanol.

The next four headings show the calculations which normalize the listed reductions in emissions to reflect the reductions that the vehicles would have achieved using a blend with 3.7% oxygen and matched volatility to the base fuel. Each of the headings indicates which group of fuels data (from among the previous three headings) is being normalized. "D psi" indicates the difference between the RVP of the blend and that of the base fuel. The effect of fuel oxygen content was calculated assuming a linear relationship between fuel oxygen level and exhaust emission changes from the base fuel. The effect of RVP on exhaust emissions was calculated using the assumptions in MOBILE3.9.

Forcing Matched RVP, Splash 10% Ethanol: These columns show the results of the adjustments for RVP that are presented in section 3.3.4. Entries to these columns only occur when the vehicles represented in a given row were tested on a splash blend of 10% Ethanol. Since there is no adjustment for NOx due to RVP, and a 10% ethanol blend should already have approximately 3.7% oxygen content, there is no column listing for NOx under this heading.

Forcing Matched RVP and Oxy for Other ~3.7 Oxy Fuels: Since the blends represented in this column do not necessarily have matched RVP to the base fuel, the VOC and CO reductions are adjusted to reflect the results of matched RVP fuels. Since the blends may have oxygen contents of other than 3.7%, the VOC, CO, and NOx results are further adjusted in proportion to the oxygen content to reflect a 3.7% oxygen content.

Forcing Matched RVP & 2% Oxygen from ~2% Ox: This heading contains entries when the group of vehicles represented in the row was tested using a fuel of about 2% oxygen content. The exhaust emissions are adjusted to reflect matched RVP and 2% oxygen content.

Forcing 3.7% Oxygen from ~2% Oxygen: Under this heading, the results of the previous heading are scaled to reflect a larger oxygen content.

Average Reductions by Study: In each entry under this heading is the average of the percentage changes in emissions as adjusted to reflect a matched RVP and 3.7% oxygen content over all of the fuels tested in the vehicles represented by this line of the table. At the bottom of each technology group is the average of these percentage figures, weighted by the number of vehicles in each study. Each gasoline/oxygenate blend within a given study receives weight equal to other fuels in the same study, even when they are represented on more than one line in the table.

Base g/mi: Under this heading are the average base fuel emission levels of the studies, weighted by the number of vehicles in each study. Averages are listed for different altitudes within each technology group, and for the combined high and low altitude results of each group. This information is useful for comparing the emission levels of vehicles in the studies to those which would be predicted of in-use vehicles. Based on this comparison, a qualitative judgement can be made regarding how well the data set represents an in-use fleet.

The following is a detailed example of the calculations involved in one of these rows for one pollutant. Study V included 2 closed loop vehicles tested at low altitude. The base (non-oxygenated) fuel used in this study had an RVP of 9.0 psi, and the average exhaust CO emissions of these vehicles was 1.88 g/mi. These vehicles were also tested with a splash blend of gasoline with 10% ethanol, which had an RVP of 9.7 psi. When using this fuel, their average CO emissions increased by 3.7%. When the vehicles were tested using a volatility adjusted blend of 10% ethanol in gasoline (RVP = 9.0 psi), their average CO emissions changed by 33.3% from the baseline levels. When they were tested on a blend with 15% MTBE, their CO emissions changed by 2.7%.

Before the results can be averaged, they must be adjusted to offset the effects of different volatilities and oxygen levels. The percentage reductions are changed to represent those that would be achieved by a blend with 3.7% oxygen content and matched volatility to the base fuel. When a splash blend of 10% ethanol in gasoline is used, the oxygen content is already approximately 3.7%, so the only adjustment that ~~is~~ made is for volatility. This RVP adjustment is made according to the equations presented in section 3.3.4 of this report.

These vehicles had closed loop fuel control systems, so their emissions are adjusted using the relationship of RVP to emissions listed for vehicles of the 1981 and later model years. For this calculation, the following values are used. The CO emissions of the vehicles when fueled with the blend were 1.037 times the emissions when the base fuel was used (or 1 + 3.7%). The base fuel RVP was 0.7 psi lower than that of the blend. To simplify the calculations at the cost of only a small error, the effect of RVP is calculated using a base value of 11.5 psi, so the difference between a 11.5 psi fuel and a 10.8 psi fuel is calculated first, and then applied to the blend emission level.

CO @ -0.7 psi

= CO (blend) * (0.18753 + 0.07065 * (11.5psi - 0.7))

= CO (blend) * 0.95055

= CO (base) * 1.037 * 0.95055

= CO (base) * 0.98572 (a reduction of 1.4%)

This operation separates the effect of the 0.7 psi difference in RVP from that of the oxygen content, now calculated to be a 1.4% decrease. For the matched volatility ethanol blend the RVP was already matched, so the matched RVP column has the same reductions as the actual test data.

In the next column test data from blends of roughly 2% oxygen are adjusted to match the RVP of the base gasoline and to have exactly 2.0% oxygen. In the case of this 15% MTBE blend, the 0.1 psi RVP adjustment and the oxygen content adjustment from 2.7 to 2.0% result in smaller effects on all three emissions. This is followed by a column in which the 2.0% oxygen numbers are proportionally adjusted up to 3.7% oxygen to make them directly comparable to the other 3.7% oxygen data. This increases the effects on VOC, CO, and NOx to -6.4%, +2.7%, and +8.8%.

The final combination of data is accomplished in the three columns labelled, "Average Reductions by Study, matched 3.7% Ox and RVP, weighted together by veh." In the row for the closed loop vehicles in Study V the adjusted effects of each of the three oxygenated fuels are combined by weighting the effects for each fuel by the number of vehicles tested on that fuel in that study, yielding a CO increase of 11.5%. The totals for each column are similarly combined by weighting the results from each study by the number of vehicles in that study. The totals for all closed-loop, pre-'84 vehicles show a CO reduction of 19.7%. The last three columns provide the base gasoline gram/mile emissions, averaged in the same way for each column. These values may be compared between different groups of vehicles within this summary as well as with in-use emission levels.

Sources of Data

The reports from which data were taken for use in these calculations are listed here. They are also listed in the Reference section of this paper, in the same order, starting with reference 4.

A. "Ethanol-Blended Fuel as a CO Reduction Strategy at High Altitude," Section C, Vol. II, Study of 10 medium heavy duty vehicles, Colorado Department of Health, August 1985.

B. "Fleet Demonstration", Colorado Department of Health, 30 vehicles, variable oxygen content, November 1987.

C. "Effects of Ethanol-Blended Fuel on Motor Vehicles at High Altitude," Colorado Department of Health, September 198[illegible] (also reported as part of Reference A).

D. "Exhaust Emissions and Fuel Economy from Automobiles using Alcohol/Gasoline Blends Under High Altitude Conditions," David Richardson, EPA, October 1978.

E. "The Effects of Two Different Oxygenated Fuels on Exhaust Emissions at High Altitude," Colorado Department of Health, January 1987.

G. EPA Ann Arbor 1987-88 In-House Gasohol Test Data as of December 1987.

H. "Exhaust and Evaporative Emissions from a Brazilian Chevrolet Fueled with Ethanol-Gasoline Blends," R. Furey and M. Jackson, GM Research Publication GMR-2403, June 1977.

J. "Analysis of Gasohol Fleet Data to Characterize the Impact of Gasohol on Tailpipe and Evaporative Emissions," (summary of nine related studies) EPA Mobile Source Enforcement Division Report, December 1978.

K. "Characterization and Research Investigation of Alcohol Fuels in Automobile Engines", Santa Clara University, prepared for DOE as DOE/CS/51737-1, February 1982.

P. "Exhaust Emissions, Fuel Economy, and Driveability of Vehicles Fueled with Alcohol-Gasoline Blends," Brinkman, Gallopoulos, Jackson, SAE Paper 750120, 1975.

R. "Evaporative and Exhaust Emissions of Two Automobiles Fueled with Volatility Adjusted Gasohol," David Lawrence and Daniel Niemczak, EPA Report EPA-AA-TEB-81-12, December 1980.

S. "Exhaust and Evaporative Emissions from Alcohol and Ether Fuel Blends," T. M. Naman and J. R. Allsup, SAE Paper 800858, 1980.

T. "Gasohol; Laboratory and Fleet Test Evaluation," M. D. Gurney, et al, SAE Paper 800892, 1980.

U. "Gasohol, TBA, MTBE Effects on Light-Duty Emissions", B. Bykowski, Southwest Research Institute, EPA Report 460/3-79-012, NTIS PB 80224082, October 1979.

V. "Evaporative and Exhaust Emissions from Cars Fueled With Gasoline Containing Ethanol or MTBE," R. Furey and J. King, SAE Paper 800261.

W. "Performance Evaluation of Alcohol-Gasoline Blends in 1980 Model Automobiles: Phase 1 - Gasoline-Ethanol Blends," CRC Report No. 527, July 1982.

X. Clean Air Act Waiver Application for Oxinol, ARCO, May 1981.

Y. Clean Air Act Waiver Application for the DuPont blend, July 11, 1984.

Z. "In-House 23 Car In-House Oxinol Blend Test Program," EPA memo from Craig Harvey to Charles Gray, ECTD, November 19, 1984.

AA. "Characterization of Emissions from Vehicles Using Methanol and Methanol-Gasoline Blended Fuels," P. Gabele et al, JAPCA Vol. 35, no. 11, 1168-1175, 1985.

AB. "A Generic Report of Toxics from Oxygenated Fuels," Colorado Department of Health, Spring 1987; Note: CDH has stated these preliminary data are released for use in our report.

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FEASIBILITY AND COST-EFFECTIVENESS OF CONTROLLING EMISSIONS FROM DIESEL ENGINES IN RAIL, MARINE, CONSTRUCTION, FARM, AND OTHER MOBILE OFF-HIGHWAY EQUIPMENT

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